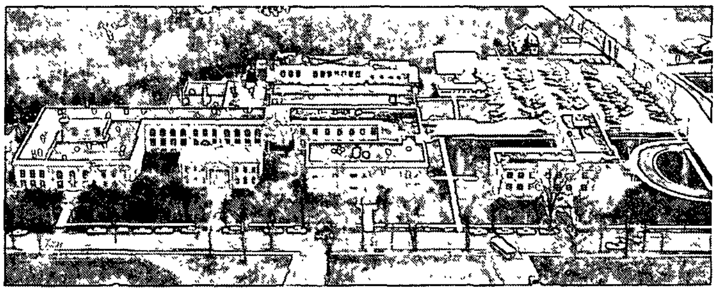

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DROPLET SIZE DISTRIBUTION OF BLACK LIQUOR SPRAYS

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Droplet Size Distribution of Black Liquor

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ABSTRACT

Spray size distribution data for splashplate and swirl cone black liquor nozzles are presented and compared to literature data on a variety of fluids and nozzles. Tests were carried out at flow rates of 0.75 to 2.5 L/S (12 to 40 GPM). Operating conditions included tests with 53% dry solids black liquor at 26°C (78°F) and 66% to 72% solids black liquor at temperature between 104°C and 127°C (220°F to 260°F). The extensive literature data have been used to show that a spray can be characterized by a mass median diameter and a normalized distribution about the median. The experimental data are used to show that this is also true for black liquor nozzles and that the distribution is square root normal. Practical applications of these results are demonstrated for the splashplate nozzle.

INTRODUCTION

Black liquor is sprayed into recovery boiler furnaces through nozzles which produce droplets ranging in size from approximately 0.1 to 5 mm. Initial black liquor droplet size has been shown to be important to droplet combustion [1] entrainment [2], and carryover [3]. Despite the importance of droplet size and size distribution to optimum recovery boiler performance and safety, only one previous study has dealt with the characterization of black liquor sprays from conventional nozzles [4]. One further study [5] has investigated black liquor droplet formation from jets using vibratory assist to produce narrow size distributions.

The purpose of this paper is to present data from two recent studies of black liquor droplet formation from conventional splashplate and swirl cone recovery boiler nozzles. These studies were carried out at two different laboratory facilities, the Alliance Research Center of the Babcock & Wilcox Co. and The Institute of Paper Chemistry. Both studies used kraft black liquor as the test fluid and used nozzles which are commercially available from the two North American recovery boiler vendors, though they were the smallest nozzles available for this purpose.

This paper is broken into four sections. The first describes the test facilities and techniques, and presents the black liquor spray size distribution data. The second demonstrates the utility of one particular distribution function for correlating the data and shows the effect of variables on the median size and size distribution. The third section discusses these results and compares them to results reported in the literature. In the final section, several general conclusions are drawn and some practical results discussed.

BLACK LIQUOR SPRAY DATA

B&W Alliance Research Center

The tests were conducted in the Atomization Facility. This facility has two 1.2 m x 2.5 m (4 ft x 8 ft) glass windows along the opposite sides of a spray booth. These windows provide optical access for the laser-based droplet sizing instrumentation. A splashplate nozzle is installed near the upstream end of the windows, about 15 cm (6 inches) above the bottom edge of the windows. The plane of the nozzle splashplate is nearly vertical, with the flow axis of the spray directed horizontally. The resulting flat vertical liquid sheet and spray occupy most of the view through the windows.

Droplet size is measured at a distance of approximately 1.2 m (4 ft) downstream of the splashplate and at three vertical locations. The initial liquid sheet breaks into droplets before reaching this distance of 1.2 m. The three vertical locations correspond to the spray centerline, the edge of the spray, and a position intermediate between these two.

The black liquor droplet size distributions were measured with a Malvern ST2600 Droplet and Particle Size Analyzer. This analyzer is particularly good at measuring the lower end of the size spectrum. This is shown in the data from a calibration test using drilled holes in brass shim stock. Table I shows the comparison of actual to measured values.

Heavy black liquor was obtained from a kraft mill at 63% solids. This liquor was diluted to 53% solids so that its room temperature viscosity was approximately 0.15 Pa-s (150 cP) simulating the viscosity of hot, as-fired black liquor at typical operating conditions. The viscosity of the liquor was measured under several conditions both before and after the spray tests. For these tests the liquor was maintained between 24°C and 27°C (76°F and 81°F).

Table I. Malvern ST2600 Analyzer Calibration.

Hole Size, mm	Measured Size, mm	Difference %
7.94	6.43	-19
2.58	2.69	+4.3
1.51	1.57	+4.0
0.89	0.858	-3.6

Two nozzles were used during the B&W Alliance Research Center study. Both were splashplate nozzles of standard B&W design. They had the same nozzle orifice size of 0.95 cm (3/8-inch), but had different splashplate angles. One was 49° and the other 35°. These nozzles were operated at three flow rates between 0.75 L/s to 1.14 L/s (12 to 18 GPM). A total of thirty five runs were carried out. Black liquor droplet size distribution data for three of the runs are shown in Figure 1. Complete specification of the test conditions and the size distribution results are presented in Table II.

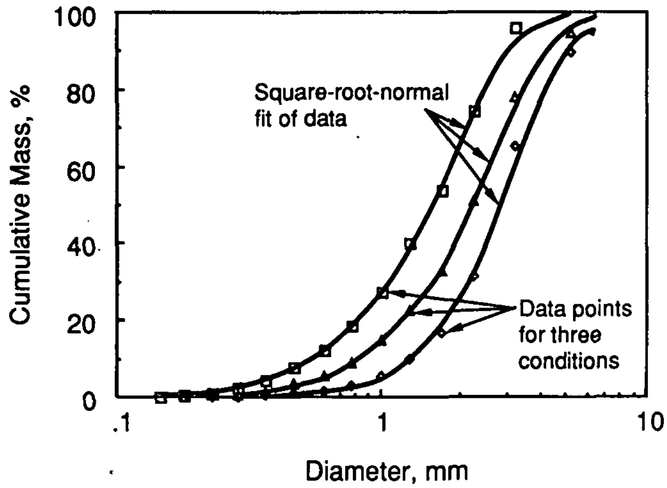

Fig. 1. Comparison of black liquor droplet size distribution data for three test conditions with corresponding square-root-normal fit of the data. Data are for B&W splashplate nozzles using the Malvern Drop Size Analyzer.

<u>The Institute of Paper Chemistry</u>

The Institute of Paper Chemistry tests were conducted in the IPC Flash X-ray Spray Facility. In this facility black liquor is sprayed downward into a catch tank. A Hewlett-Packard 43731A 150 kV flash x-ray source is aimed horizontally through the spray toward a sheet of Kodak DEF x-ray film. The black liquor droplets absorb more of the x-rays than the surrounding

Table II. Data from B&W Alliance Research Center.

Nozzle Type	Size, inch	Splashplate angle, °	Spray Location	Solids, %	Temp., °F	Viscosity, cP	Flow, GPM	Max. Vel., ft/s	Mass Median Dia., mm	Standard Deviation	Normalized Std. Dev.
B&W	0.375	49	center	53	78	150	12	36	2.19	0.468	0.316
B&W	0.375	49	center	53	78	150	15	45	1.54	0.380	0.307
B&W	0.375	49	center	53	78	150	18	52	1.69	0.406	0.312
B&W	0.375	49	center	53	78	150	18	52	1.54	0.362	0.292
B&W	0.375	49	center	53	78	150	15	45	1.41	0.348	0.293
B&W	0.375	49	edge	53	78	150	18	52	1.70	0.378	0.290
B&W	0.375	49	edge	53	78	150	18	52	1.61	0.349	0.275
B&W	0.375	49	edge	53	78	150	15	45	2.36	0.465	0.302
B&W	0.375	49	edge	53	78	150	15	45	2.21	0.424	0.285
B&W	0.375	49	edge	53	78	150	12	36	1.88	0.318	0.232
B&W	0.375	49	edge	53	78	150	12	36	2.37	0.446	0.290
B&W	0.375	49	intermed.	53	78	150	12	36	2.12	0.423	0.290
B&W	0.375	49	intermed.	53	78	150	12	36	2.09	0.417	0.288
B&W	0.375	49	intermed.	53	78	150	15	45	1.89	0.437	0.318
B&W	0.375	49	intermed.	53	78	150	15	45	1.93	0.447	0.322
B&W	0.375	49	intermed.	53	78	150	18	52	1.86	0.433	0.317
B&W	0.375	49	intermed.	53	78	150	18	52	1.70	0.397	0.304
B&W	0.375	35	intermed.	53	78	150	12	36	2.80	0.402	0.240
B&W	0.375	35	intermed.	53	78	150	12	36	2.85	0.414	0.245
B&W	0.375	35	intermed.	53	78	150	15	45	2.18	0.427	0.289
B&W	0.375	35	intermed.	53	78	150	15	45	2.19	0.435	0.294
B&W	0.375	35	intermed.	53	78	150	18	52	1.74	0.383	0.290
B&W	0.375	35	intermed.	53	78	150	18	52	1.74	0.379	0.287
B&W	0.375	35	edge	53	78	150	18	52	2.17	0.449	0.305
B&W	0.375	35	edge	53	78	150	18	52	2.24	0.446	0.298
B&W	0.375	35	edge	53	78	150	15	45	2.43	0.398	0.255
B&W	0.375	35	edge	53	78	150	15	45	2.55	0.407	0.255
B&W	0.375	35	edge	53	78	150	12	36	2.69	0.383	0.234
B&W	0.375	35	edge	53	78	150	12	36	2.84	0.388	0.230
B&W	0.375	35	center	53	78	150	12	36	2.81	0.419	0.250
B&W	0.375	35	center	53	78	150	12	36	2.76	0.409	0.246
B&W	0.375	35	center	53	78	150	15	45	2.47	0.518	0.329
B&W	0.375	35	center	53	78	150	15	45	2.39	0.496	0.321
B&W	0.375	35	center	53	78	150	18	52	1.82	0.402	0.298
B&W	0.375	35	center	53	78	150	18	52	1.83	0.408	0.301
										Average =	0.286
										%Max. =	115%
										%Min. =	81%

air and therefore leave a shadow on the exposed film. The use of flash x-ray to image a variety of flows has been discussed by Farrington [6]. A typical x-ray shadowgraph for the spray from a B&W splashplate nozzle is shown in Figure 2. The flash x-ray system is located approximately 0.9 m (3 ft) below the nozzle for B&W nozzles and approximately 0.6 m (2 ft) for CE nozzles. It is apparent from Figure 2 that the liquid sheet and ligaments of black liquor have not completely broken into droplets at this location.

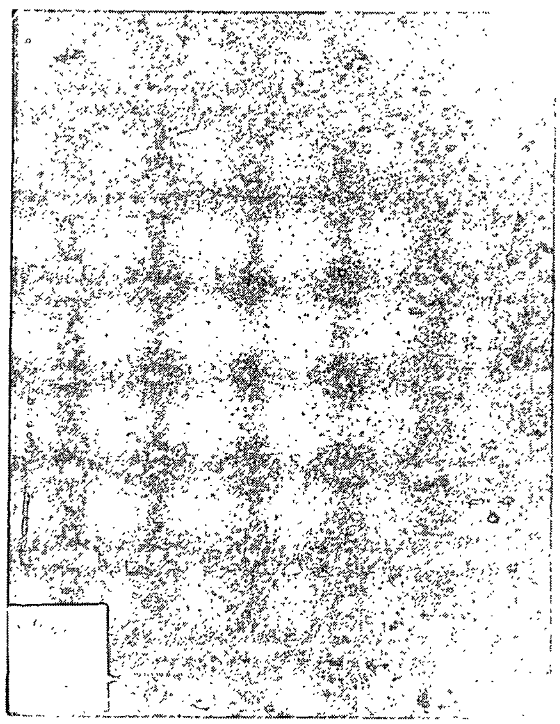

Fig. 2. Shadowgraph image for a black liquor spray using the IPC flash X-ray Imaging System.

Heavy black liquor was obtained from a kraft mill. The chemical makeup of the liquor was obtained and the viscosity determined for a variety of conditions which spanned the normal operating range for the mill. The oxidation state of the sulfur was monitored during the test program in order to observe changes in the nature of the liquor when it was sprayed and recycled back to the storage tank. No clear trend could be observed from this data. The range of conditions selected for these spray tests covered the usual range of solids and temperature for many kraft mills, 66-72% dry solids and 104°C to 127°C (220°F to 260°F). This corresponded to a viscosity range of 29 cP to 66 cP. Three nozzles were used in these tests. One nozzle was identical to the 0.95 cm (3/8 inch) 49° B&W splashplate nozzle used in the tests at the B&W Alliance Research Center. A second B&W splashplate nozzle was used which had a nozzle orifice 1.27 cm (0.5 inch) in diameter and a splashplate angle of 49°. The third nozzle was a CE swirl cone nozzle. This nozzle had an exit orifice of 1.27 cm (0.5 inch) but contained a standard internal swirl block consisting of two spiral grooves which impart the swirl to the black liquor flow just ahead of the exit orifice. The total open flow area of these two grooves is equivalent to the area of a 0.95 cm (3/8 inch) diameter hole. This is the minimum flow area for the nozzle and therefore the location of the maximum fluid velocity. This equivalent diameter will be used as the characteristic dimension for the nozzle.

For the B&W nozzles data were taken along the centerline of the spray. For the CE nozzle a mechanical catcher was used to divert a portion of the spray cone out of the field of view of the x-ray system. As a result the x-ray only passed through the spray sheet once, as with the flat B&W splashplate sprays.

The images of the sprays on the shadowgraphs were analyzed with a Trapix 55/512 image analyzer. Between 2000 and 4000 drops were examined for each condition. Droplets smaller than 0.5 mm were not included in the automatic analysis of these shadowgraphs so there is an artificial lower limit at 0.5 mm which is apparent in the three size distribution data sets presented in Figure 3. The potential effect of this lower limit will be discussed below. A complete set of operating specifications and results for the eight test conditions is presented in Table III.

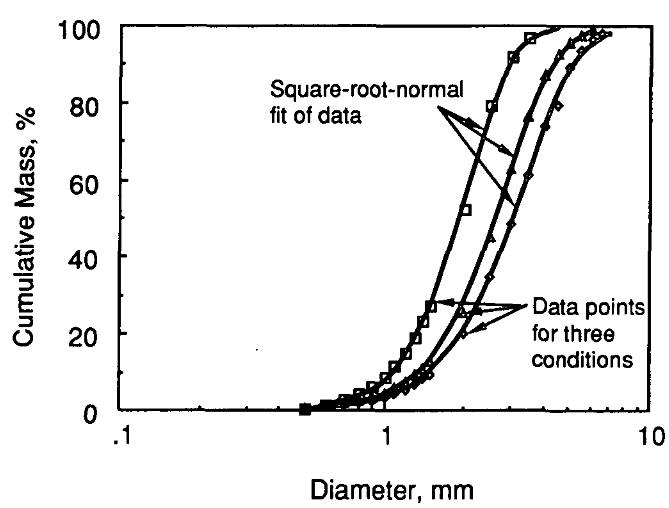

Fig. 3. Comparison of black liquor droplet size distribution data for three test conditions with corresponding square-root-normal fit of the data. Data are for CE swirl cone nozzles using the x-ray shadowgraph technique.

Table III. Data from The Institute of Paper Chemistry.

Nozzle Type	Size, inch	Splashplate angle, °	Spray Location	Solids, %	Temp., °F	Viscosity, cP	Flow, GPM	Max. Vel., ft/s	Mass Median Dia., mm	Standard Deviation	Normalized Std. Dev.
CE	0.375	cone	--	67	250	36	20	58	3.06	0.404	0.231
CE	0.375	cone	--	67	250	36	26	76	2.27	0.329	0.218
CE	0.375	cone	--	67	260	29	20	58	1.90	0.269	0.195
CE	0.375	cone	--	67	260	29	27	78	1.74	0.246	0.187
CE	0.375	cone	--	72	260	66	20	58	3.03	0.429	0.247
CE	0.375	cone	--	72	260	66	28	81	2.63	0.349	0.215
B&W	0.375	49	center	66	220	56	17	49	2.80	0.414	0.248
B&W	0.375	49	center	66	240	37	22.5	65	2.99	0.491	0.284
B&W	0.5	57	center	66	220	56	30	49	2.58	0.373	0.232
B&W	0.5	57	center	66	240	37	40	65	3.26	0.518	0.287
										Average =	0.234
										%Max. =	122%
										%Min. =	80%

CORRELATION FOR MASS MEDIAN DIAMETER AND STANDARD DEVIATION

Characterizing the data curves in terms of only a few parameters can be very useful in determining the effects of nozzle geometry and operating conditions on droplet size distribution. Several distribution curves have been suggested including log-normal, square root-normal, and Rosin-Rammler. For pressure atomizers and two-fluid atomizers the square root-normal distribution has been the most successful [7]. This distribution has the form:

$$f(D) = \frac{1}{s2\pi} \exp\left\{-\frac{(D^{1/2}-(MMD)^{1/2})^2}{2\ s^2}\right\}$$

where
- $f(D)$ = distribution function
- D = droplet diameter
- MMD = mass median diameter
- s = standard deviation

The square root-normal distribution fits the data for the black liquor nozzles used in both sets of tests as is demonstrated in Figures 1 and 3. The applicability of the square root-normal distribution to the data allows each of the size distribution curves to be represented by just two parameters, the mass median diameter, MMD, and the standard deviation, s. These values are included for each test run in Tables II and III, along with another parameter formed from them, the normalized standard deviation. For the square root normal distribution, the normalized standard deviation is defined as:

$$S' = \frac{S}{\sqrt{MMD}}$$

This latter parameter is a better measure of the breadth of the size distribution because it removes the effect of the median size.

For the spray data from the B&W Alliance Research Center the black liquor properties such as percent solids, temperature, and viscosity were not varied so it is easy to determine the effects of the other variables: splashplate angle, spray location, and flow velocity. The effects of these variables on the mass median diameter and the normalized standard deviation are shown in Figures 4 and 5.

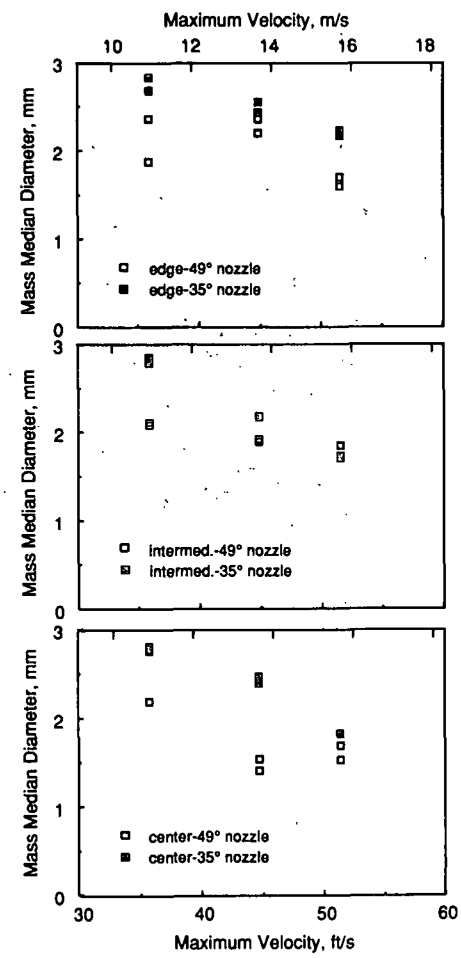

Fig. 4. Mass median droplet diameter of black liquor sprays from B&W nozzles as a function of maximum nozzle velocity for three spray locations and two splash-plate angles.

As can be seen in Figure 4, there is relatively little scatter between duplicate runs, the 35° splashplate produces a larger mass median spray size for given conditions compared to the 49° splashplate, and the spray becomes finer as flow is increased. Though some of the curves in Figure 4 appear to be nearly linear, there is enough curvature in others to make any specific conclusion difficult.

Quite a different picture emerges from Figure 5. Only relatively small deviation from an overall average value is seen for the normalized standard deviation and no clear trend is apparent. From this it can be inferred that the size distribution about the median does not change appreciably under conditions which do change the MMD by nearly a factor of two. This point will be discussed further below.

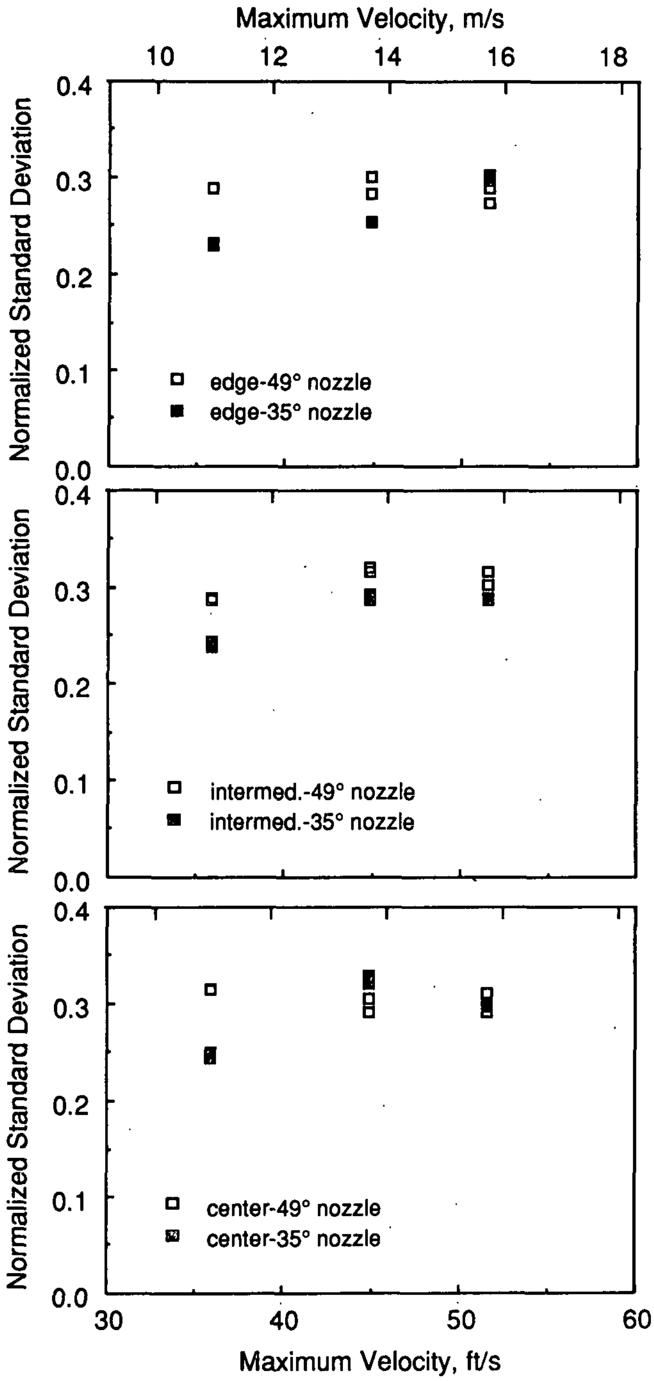

Fig. 5. Normalized standard deviation of black liquor sprays from B&W nozzles as a function of maximum nozzle velocity for three spray locations and two splash-plate angles.

DISCUSSION

The extensively developed literature on droplet formation and spray nozzles indicates there are many variables which affect the ultimate size distribution. These variables include nozzle geometry, nozzle size, liquid flow rate, fluid properties, and measurement location. The data from the present two studies and from a previous study of black liquor sprays [4] are too limited to clearly establish the impact of any one of these parameters on black liquor sprays in recovery furnaces. However, the present results are consistent with several aspects of previous observations of spray performance. The most important result from the present work is that practical advantage can be taken of the dependence of spray size on flow velocity. The results presented in Figure 5 show that the normalized size distribution for the spray is not strongly affected by flow velocity. This means that the fraction of droplets below a given size can be reduced by increasing the mass median size. This is demonstrated in the three curves of Figure 1. The mass of droplets smaller than 1 mm decreases substantially for the conditions which produce larger values of mass median diameter. Though there is still considerable uncertainty about the size of droplets which produce carryover and boiler pluggage [2], it is clear that reduced entrainment can reduce carryover. Avoiding the production of undersized droplets by avoiding small values of MMD is one approach to doing this.

Bennington [8] summarized the results of many previous spray characterizations which show the mass median droplet diameter decreases approximately with the square root of the flow velocity. Bennington's work with small swirl cone nozzles and black liquor also showed a decrease with flow velocity raised to the 0.54 power. The data of the current study are too limited for a good correlation. However, the data of Figure 4 show the trend that higher flow velocity produces smaller values of MMD. Using larger nozzles for a given black liquor flow rate would reduce the flow velocity and increase the MMD. Considering the limited extent of this data and the need to avoid char bed blackout, caution would have to be used in testing oversized liquor nozzles on an operating recovery boiler. Spray size distribution data are usually badly scattered and specific conclusions about correlations may be statistically correct but may not accurately describe a specific nozzle or condition.

The basic feature of sprays which allows control of undersized droplets is the insensitivity of the normalized size distribution to system and operating parameters. The data of Figure 5 show the variation for various test conditions. From Table II the average value for all the conditions is 0.286. The maximum value is 15% greater than this and the minimum value is 19% less than this.

The values in Table II are for one nozzle type (B&W splashplate), one black liquor, and one measurement technique. Bennington used water, glycerol, and black liquor with very small swirl cone nozzles and obtained droplet size distributions with average normalized standard deviation of about 0.30. The maximum was 20% greater and the minimum 19% smaller.

Simmons [7] reported very extensive data on small pressure atomized nozzles using a range of fuel oils. This data covered more than two thousand tests of one hundred nozzles using fuels which spanned the range of viscosity from 0.001 to 0.02 Pa-s (1 to 20 cp). Two data acquisition techniques were employed, frozen wax-droplet and optical recording with subsequent image analysis. The average value for the normalized standard deviation of all the tests was 0.24 with a maximum 17% greater and minimum 20% smaller.

Finally, the eight tests with hot black liquor at IPC listed in Table III show a normalized standard deviation for all three nozzles and all test conditions of 0.234 with a maximum 22% greater and minimum 20% smaller. This value of normalized standard deviation is smaller than that calculated for the Alliance data (0.286) and that of Bennington (0.3). This may be caused by the artificial minimum droplet size of 0.5 mm. Omitting the smaller droplets tends to increase the MMD while reducing the standard deviation, thereby decreasing the value of the normalized standard deviation.

In each of the four studies there is no obvious correlation of the normalized standard deviation with any of the operating parameters. The data of Figure 5 appear to be typical. The numerical value of normalized standard deviation is slightly different for each of the studies, but the statistical scatter in its value is very similar. At this point it is not possible to conclude whether system and analysis technique or actual nozzle and fluid parameters affect its value. Regardless of the cause of the differences, the data support the use of oversized nozzles for carryover control in recovery boilers.

What is most surprising from the data of Table III is the similarity of the droplet size distribution from the splashplate and swirl cone nozzles. This is supported by the comparison of the Alliance Research Center and the Bennington data as well as by the direct comparisons within the IPC data. The similarity of the MMD between similarly sized nozzles at similar flow velocities is also surprising, but this may be an artifact of the IPC data. The IPC data were taken at a spray location closer to the nozzle than for the other studies. Incomplete droplet formation is evident in Figure 2. This along with the artificial lower limit of 0.5 mm in the analysis of these data would tend to move the droplet size distribution toward larger drop sizes. This is evident in comparing data on the 49° B&W splashplate nozzle taken at the Alliance Research Center and IPC. Considerably more data will be required before conclusions can be drawn about the performance of these two nozzles.

An important additional observation from these tests which is not reflected in the data concerns spray stability. The reported data are for conditions which produced good droplet formation. In both tests programs very poor droplet formation occurred at conditions not too far removed from those reported. The potentially hazardous condition of black liquor roping reported by mill operators will depend on fuel and operating parameters. Maps of nozzle operating stability would be extremely useful results accompanying further tests of black liquor spray size distribution.

CONCLUSIONS

Two recent test programs have added considerably to the data base of black liquor nozzle performance. Conclusions which can be drawn from this work are:

1. A square root-normal size distribution function provides very good correlations of black liquor spray size distributions. This is consistent with previous spray studies of black liquor and other fluids and allows characterization of size distribution with only two parameters, the mass median drop diameter and the normalized standard deviation.
2. Available spray data indicate that the normalized size distribution doesn't change, or changes very little, as a function of nozzle geometry, flow conditions, and fluid parameters.
3. Both the available black liquor data on droplet size distribution and the insensitivity of normalized standard deviation lead to a practical approach to control of undersized droplets. Oversized nozzles give lower flow vel-

ocities for a given black liquor flow. This results in a larger mass median droplet diameter and a lower fraction of undersized droplets. Cautious use of this approach is needed to avoid unstable nozzle operating conditions which cause poor droplet formation conditions.

4. There is still insufficient data on black liquor spray nozzles to draw conclusions about the impact of nozzle geometry and fluid properties.
5. More data are needed on conditions which produce stable nozzle operation and good droplet formation before droplet correlations can be used confidently in mill operations.

ACKNOWLEDGMENTS

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